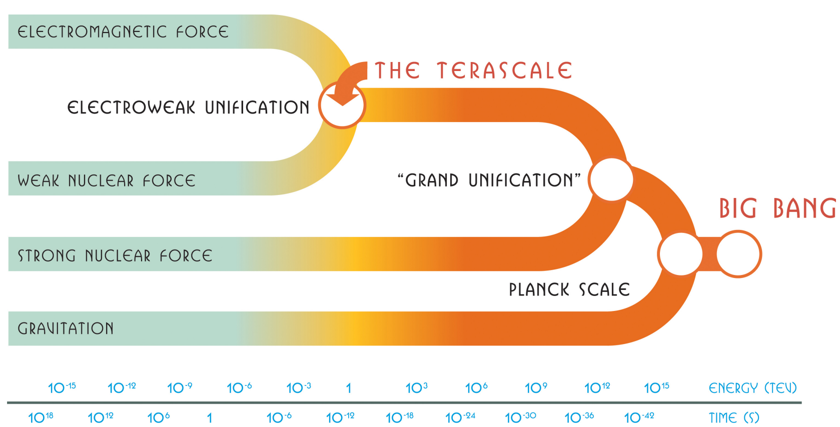
The Search for the Next Scale

After the Higgs: What next?

S. Dawson, BNL

February 12, 2014



New York Times, July 5, 2012

Physicists Find Elusive Particle Seen as Key t erse

What comes after the euphoria?

POOL PHOTO BY DENIS BALIBOUSE

Scientists in Geneva on Wednesday applauded the discovery of a subatomic particle that looks like the Higgs boson.

A Long Journey

BROKEN SYMMETRY AND THE MASS OF GAUGE VECTOR MESONS*

F. Englert and R. Brout
Faculté des Sciences, Université Libre de Bruxelles, Bruxelles, Belgium
(Received 26 June 1964)

BROKEN SYMMETRIES, MASSLESS PARTICLES AND GAUGE FIELDS

P. W. HIGGS
Tait Institute of Mathematical Physics, University of Edinburgh, Scotland

Received 27 July 1964

VOLUME 13, NUMBER 16 PHYSICAL REVIEW LETTERS 19 OCTOBER 1964

BROKEN SYMMETRIES AND THE MASSES OF GAUGE BOSONS

Peter W. Higgs
Tait Institute of Mathematical Physics, University of Edinburgh, Edinburgh, Scotland
(Received 31 August 1964)

GLOBAL CONSERVATION LAWS AND MASSLESS PARTICLES*

G. S. Guralnik,† C. R. Hagen,‡ and T. W. B. Kibble
Department of Physics, Imperial College, London, England
(Received 12 October 1964)

Decades of Theory

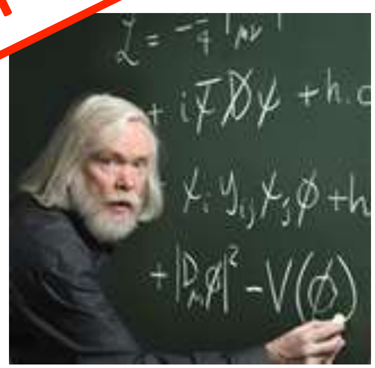
A PHENOMENOLOGICAL PROFILE OF THE HIGGS BOSON

John ELLIS, Mary K. GAILLARD * and D.V. NANOPOULOS **
CERN, Geneva

Received 7 November 1975

A discussion is given of the production, decay and observability of the scalar Higgs
boson H expected in gauge theories of the weak and electromagnetic interactions such as
the Weinberg-Salam model. After reviewing previous experimental limits on the mass of
the Higgs boson, we give a speculative cosmological argument for a small mass. If its m
is similar to that of the pion, the Higgs boson may be visible in the reactions π^-
$\gamma p \to Hp$ near threshold. If its mass is $\lesssim 300$ MeV, the Higgs boson may be
decays of kaons with a branching ratio $O(10^{-7})$, or in the decays of
ticles: $3.7 \to 3.1 + H$ with a branching ratio $O(10^{-4})$. If its ma
boson may be visible in the reaction $pp \to H + X$, $H \to \mu^+$
$\leqslant 2m_\mu$, the decays $H \to e^+e^-$ and $H \to \gamma\gamma$ dominate
2×10^{-12}) seconds. As thresholds for heavi ar-
ticles) are crossed, decays into them be rapidly
to $O(10^{-20})$ sec for a Higgs boso in principle
enable the quark masses to

Understanding what we're looking for



Fermi National Accelerator Laboratory

FERMILAB-Pub-84/17-T
LBL-16875
DOE/ER/01545-345
February, 1984

SPIRES: find t Higgs
13,214 papers

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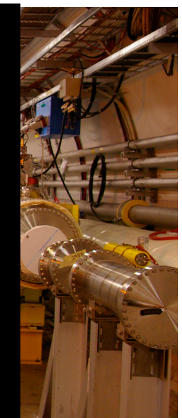
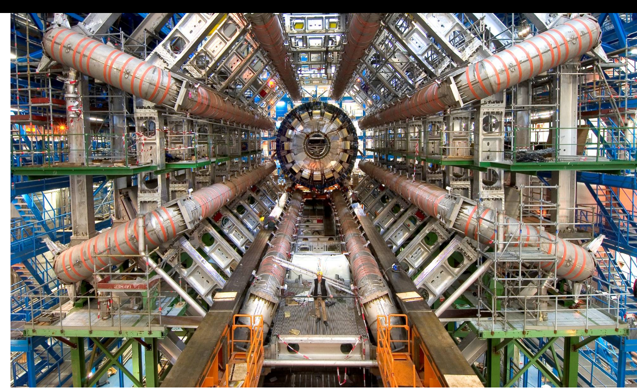
Decades of Effort

- Theory: 1964

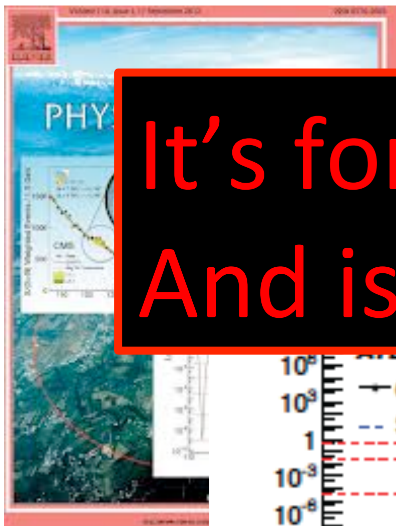
Three vital ingredients: Accelerator, Detectors, Theory

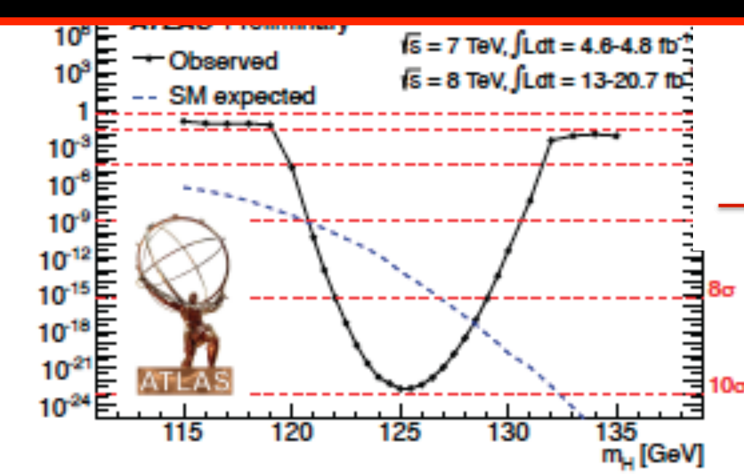




We discovered a Higgs boson!

- The Standard Model is very predictive *(testable!)*
- Only free parameter is M_h





It's for real. But is it THE Higgs?
And is there more? What next?

CMS

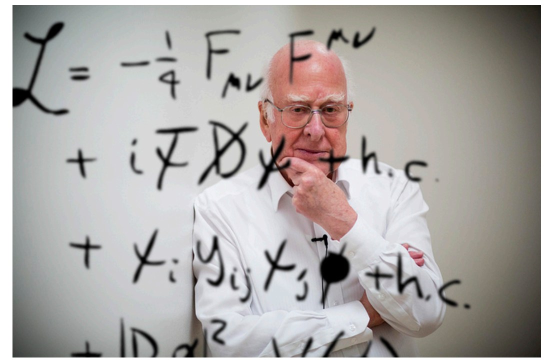
bb	**2.2 σ**	**2.1 σ**
ττ	3.4σ	3.6σ

Both ATLAS and CMS have close to 10σ significance

Probability of 10 σ event being random is 10^{-23}

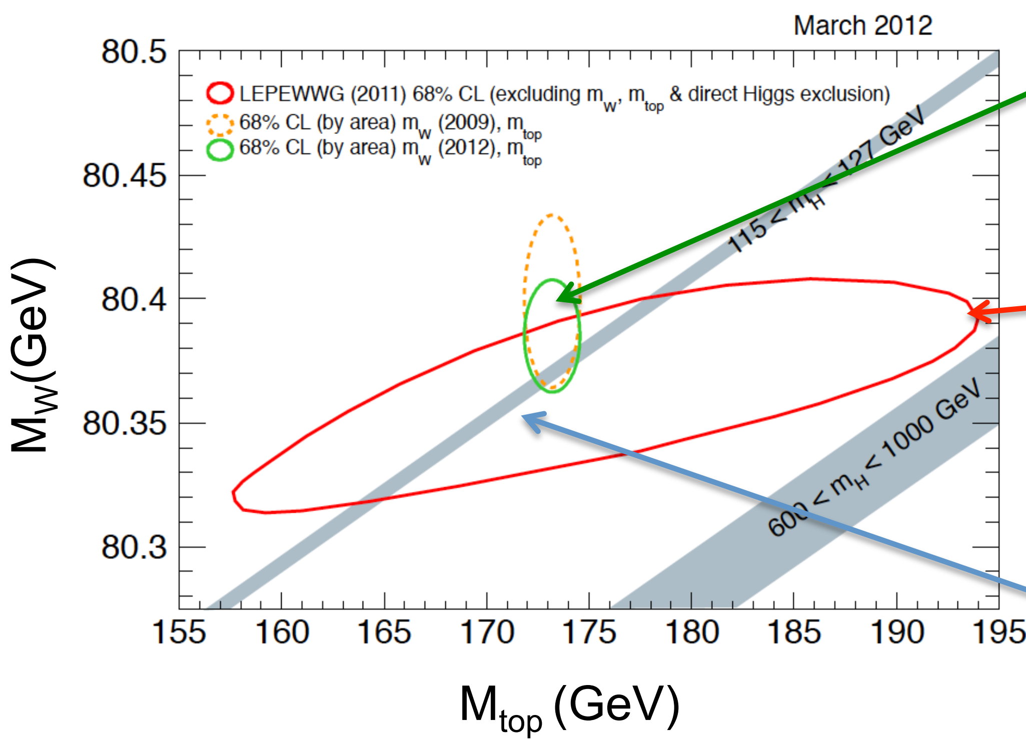
Important Higgs Facts:

- Higgs couplings are proportional to mass:
  - Higgs coupling to top is m_t/v
  - Higgs coupling to W is gM_W



- Predict experimental quantities in terms of Higgs mass:
  - A consistent framework for calculations
  - Without the Higgs, M_W prediction would be infinite
  - M_W=(known stuff)+(….)m_t^2/M_W^2+ (…)$\log(M_h^2/M_W^2)$

Precision Physics Before Higgs Discovery



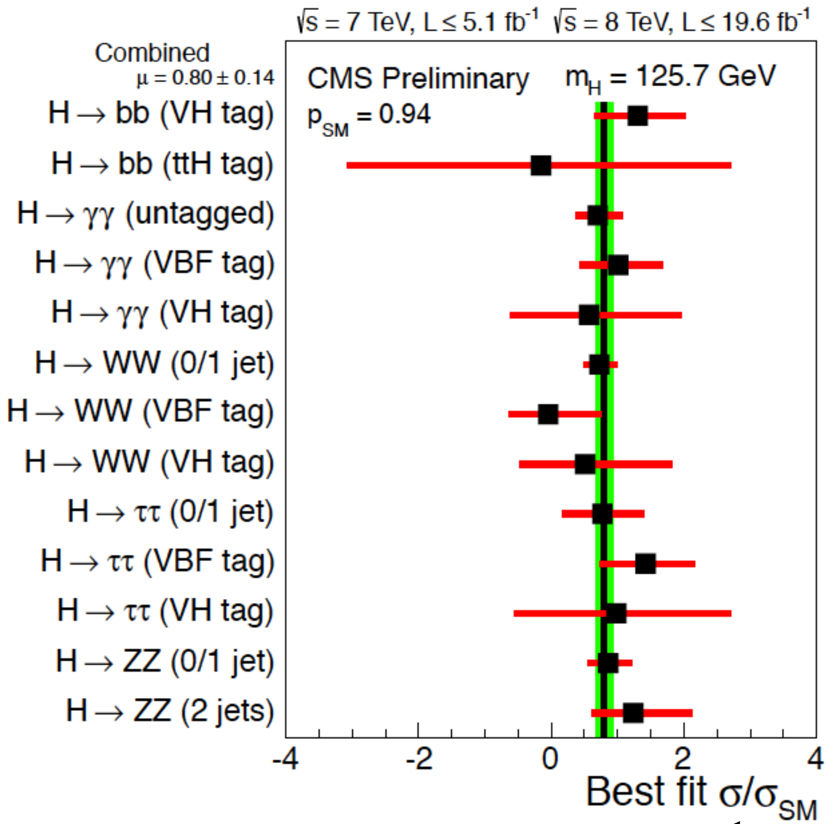
Experimental measurements from Fermilab

Inferred values of M_W and M_t from other experiments

Theory predictions

Self-consistency of the theory told us the Higgs couldn't be too heavy without new physics

Data Consistent with SM Hypothesis



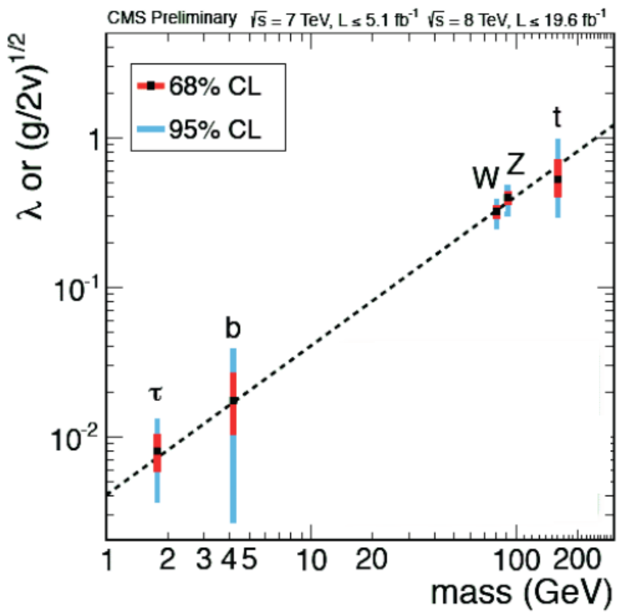
Couplings to both fermions and gauge bosons observed with rates which are consistent with predictions

CMS : Data/theory = 0.80± 0.14
ATLAS : Data/theory =1.23± 0.18

Lots of theory dependence in the denominator!

Higgs Couples to Mass!

- Very precise predictions
  - Couplings to fermions proportional to mass
  - Couplings to gauge bosons proportional to mass
  - Higgs self-couplings proportional to M_h^2



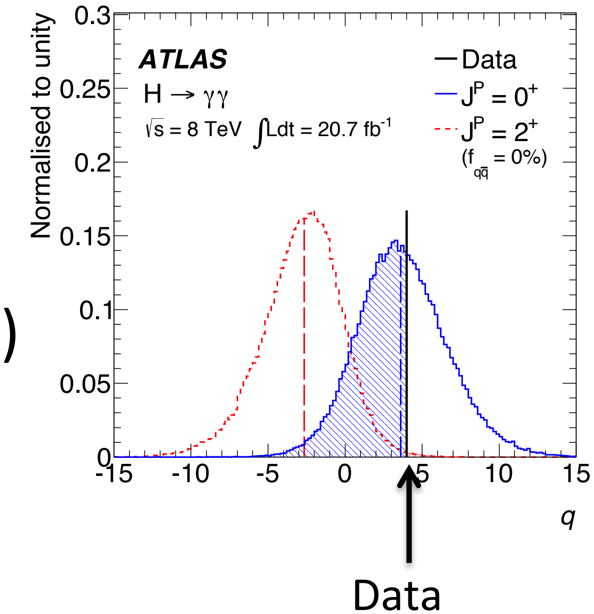
Couplings must have this pattern if model is correct

*t coupling inferred from ggh top loop production rate

What We Know

H → γγ :

- H is electrically neutral
- H is likely to be spin-0
- H cannot be spin-1 (Yang's theorem)
- H can be spin-2 (disfavored)



H → ZZ, W^+W^- :

- Quantum numbers consistent with Higgs giving mass to W and Z

$$\phi^\dagger \phi Z_\mu Z^\mu \rightarrow h < h > Z^\mu Z^\nu$$

Needed Something like a Higgs

- The Higgs particle interactions need to explain:
  - Non-zero mass of W and Z gauge bosons
  - Non-zero mass of fermions
  - Consistency of low energy measurements
    - The theory would give infinity without a Higgs-like object
- Precision electroweak data (such as the Tevatron measurement of the W mass) is consistent with SM

*So the fact that the observed Higgs particle looks **SM-like** is no surprise*

The SM can't be complete

- It doesn't explain:
  - Neutrino masses
  - The pattern of fermion masses
  - Dark matter
  - Baryon asymmetry

If new physics explains any of this, how do we get a handle on the relevant energy scale?

The bottom line: The Higgs boson looks SM like and we haven't found any other new particles…..but we expect them soon……

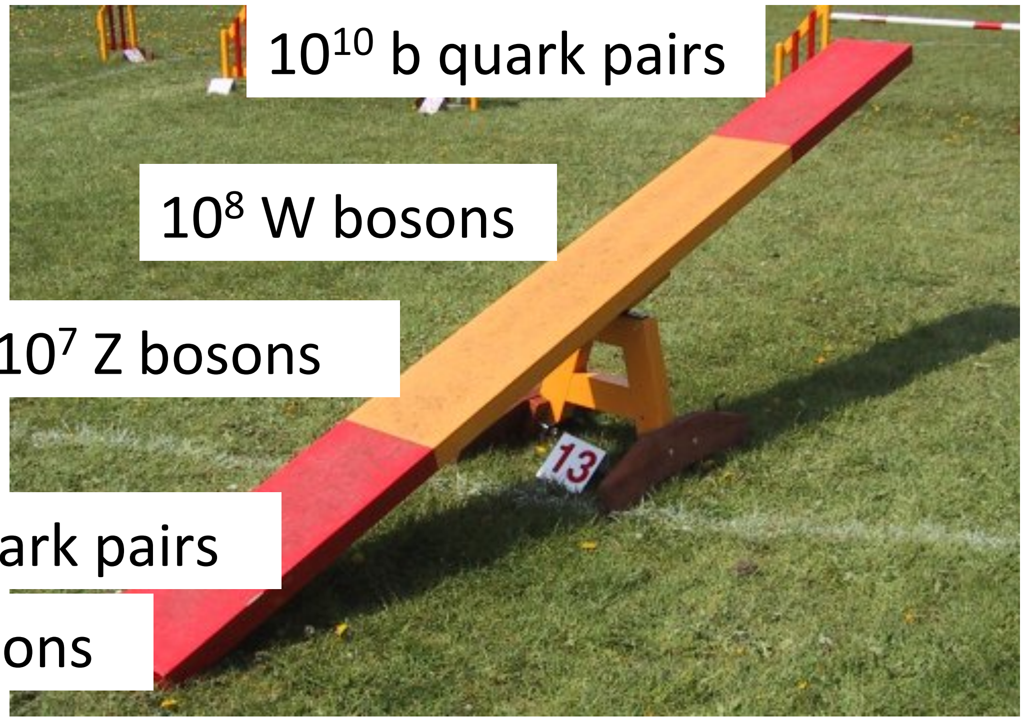
The Future Precision Higgs Program

- Higgs Properties
  - Mass/width (Mass is a free parameter; width is predicted)
  - Spin-parity (predicted)
  - Couplings (predicted)
- Search for new Higgs-like particles

We are entering the next discovery phase of Higgs physics

How Rare is a Higgs?

- The LHC has made:



10^{10} b quark pairs

10^{8} W bosons

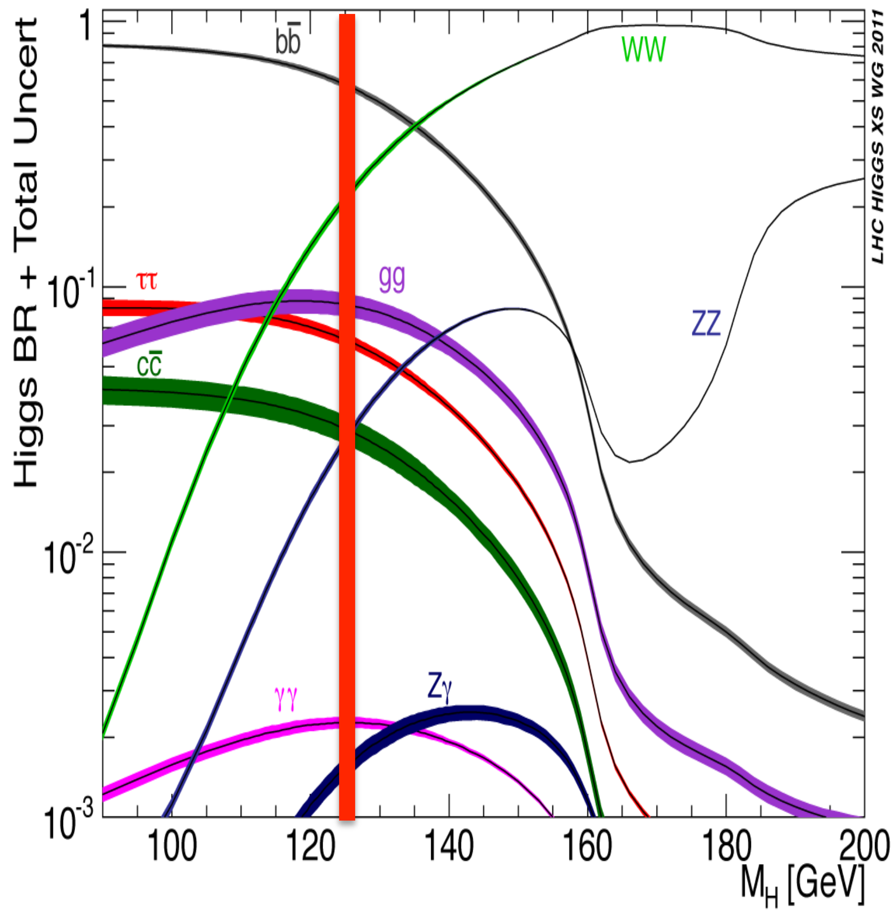
10^{7} Z bosons

10^{5} top quark pairs

10^{5} Higgs bosons

1 Higgs for every 100,000 b quark pairs

M_h=125 GeV Ideal for Experiment

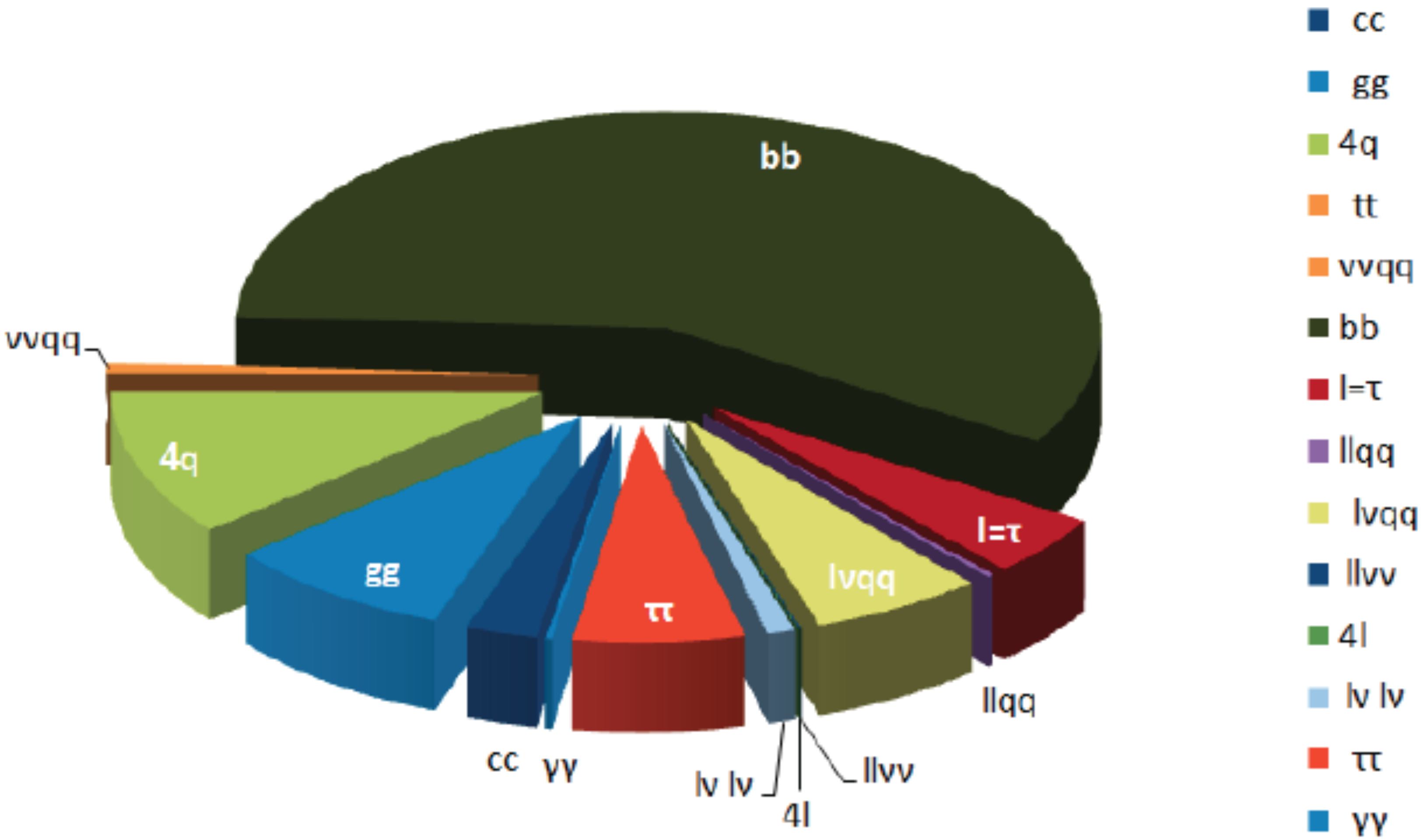


Can measure many decay channels

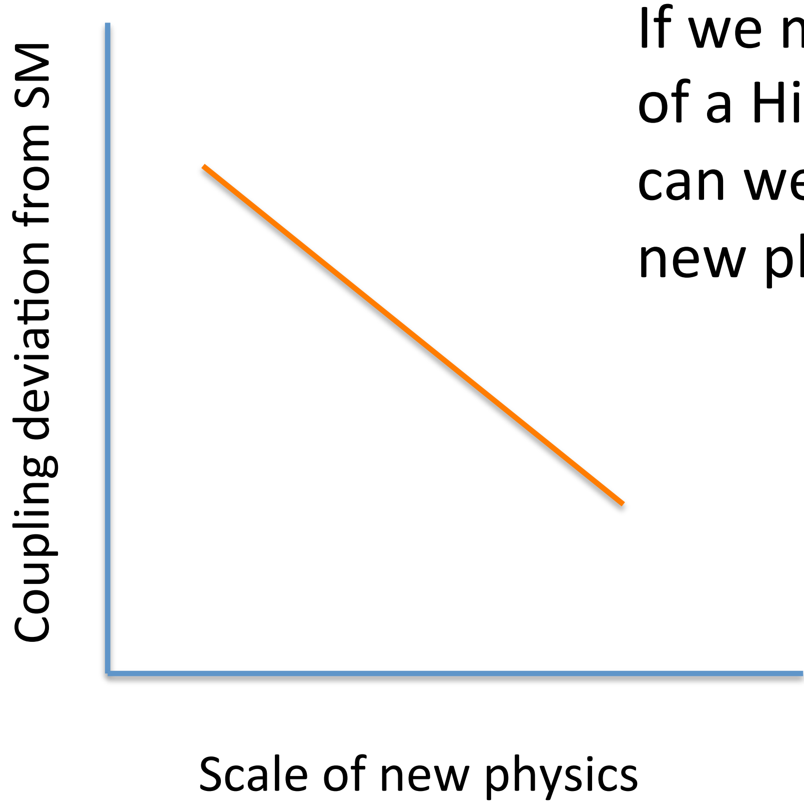
- Most of the time the Higgs decays to b quarks
- Have observed the rarer decays (γγ,ττ,WW,ZZ)

Need more data!

Where does the Higgs go?



What we hope for



If we measure a large deviation of a Higgs coupling from the SM, can we associate it with a scale of new physics?

Proof by exhaustion

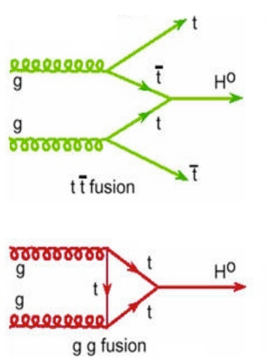
For this to work, we have to understand the SM first (Remember precision measurements at LEP!)

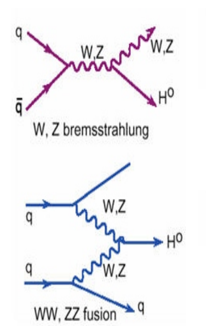
Precision Higgs Production

Theory uncertainties in Higgs production at 14 TeV

	Scale	PDF + a_s	Total (linear sum)
ggF	+12, -8%	±7%	+20, -15%
tth	+6, -9%	±9%	+15, -18%
VBF	+.7, -.4%	+2, -2.6%	±3%
VH	+.3, -.6%	±4%	±4%

Need to improve SM calculations and their inputs (especially PDFs) as we enter a new era of precision Higgs physics





Precision Measurements vs Direct Observation of New Particles

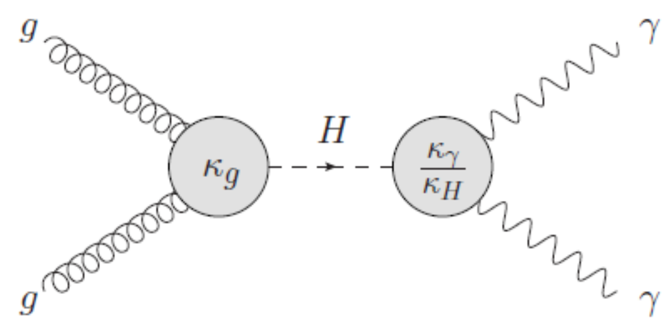
- Is there a clear answer to how precisely we need to measure Higgs couplings to get insight into new physics?
- If new particles are excluded to some scale, what does that tell us about the target for measuring Higgs couplings?

Report of Snowmass Higgs Working Group, Dawson, Gritsen, Logan, Qian, Tully, van Kooten, arXiv: 1310.8361

Measure Deviations from Predictions

- Current LHC measurements constrain Higgs couplings to ~20-30% deviations from predictions
- Scale Higgs couplings by fudge factors,
  - *κ (=1 in Standard Model)*
- Look at 10 year plan (300 fb^{-1}) and 20 year plan (3000 fb^{-1})

Example:
$gg \to H \to \gamma\gamma$



LHC Coupling Projections

- Different scenarios assumed by CMS and ATLAS
  - ATLAS: with and without theory error (same syst.)
  - CMS: (a) Same systematics as today and (b) systematics scales as $1/\sqrt{L}$ and theory error halved

		κ_γ	κ_W	κ_Z	κ_g	κ_b	κ_t	κ_τ	$\kappa_{Z\gamma}$	κ_μ
300fb^{-1}	ATLAS	[8,13]	[6,8]	[7,8]	[8,11]	N/a	[20,22]	[13,18]	[78,79]	[21,23]
	CMS	[5,7]	[4,6]	[4,6]	[6,8]	[10,13]	[14,15]	[6,8]	[41,41]	[23,23]
3000fb^{-1}	ATLAS	[5,9]	[4,6]	[4,6]	[5,7]	N/a	[8,10]	[10,15]	[29,30]	[8,11]
	CMS	[2,5]	[2,5]	[2,4]	[3,5]	[4,7]	[7,10]	[2,5]	[10,12]	[8,8]

ECFA, 2013

Ultimately, 2-5% measurements

How well do we *NEED* to measure Higgs Couplings?

- LHC measures $\sigma \cdot BR$ (products of couplings)

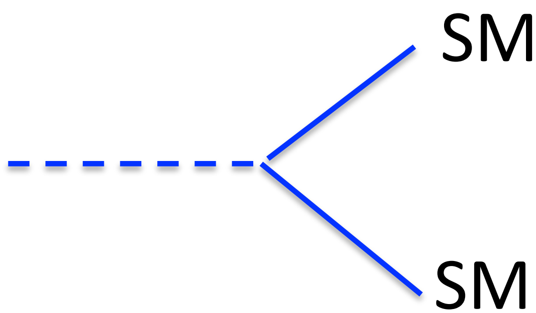
0^{th} order answer: We found a new particle which we hypothesize is the quanta of EWSB. We want to measure couplings as precisely as possible

1^{st} order answer: Let's see what kind of deviations we might expect in reasonable scenarios

- To be sensitive to deviation Δ, need to measure to $\Delta/3$ or $\Delta/5$

Additional Higgs Singlet

- Models to explain dark matter, flavor often have more than 1 Higgs boson
  - Simple example: SM Higgs mixed with electroweak singlet, S



Coupling to light Higgs, h ~ cos θ
Coupling to heavy Higgs, H ~ sin θ

- Universal rescaling of Higgs couplings, $\kappa_F = \kappa_V = \cos\theta$

Measure Higgs couplings and/or look for heavy Higgs

Complementary Approaches

- Find the heavier Higgs and/or measure deviations in couplings
- What is largest sin θ such that we won't see H (heavier Higgs) at LHC with 100 fb^{-1}?
  - For M_H=1.1 TeV expect 13 signal events, 7 background ($S/\sqrt{B}\sim5$)
  - To see new physics (without observing H) need $(\sin\theta)^2 < .12$

Target precision: $\delta\kappa \sim -\frac{\sin^2\theta}{2} \sim -6\%$

[Gupta, Rzehak, Wells, arXiv:1206.3560]

Some Possibilities

- Assume new physics (M) is at 1 TeV:
  - Typical effects on Higgs couplings $\delta\kappa \sim (M_Z/M)^2$
  - The pattern of deviations is what pinpoints new physics

Model	$\delta\kappa_W$, $\delta\kappa_Z$	$\delta\kappa_b$	$\delta\kappa_\gamma$
Singlet Mixing	~-6%	~-6%	~-6%
2HDM	~1%	~10%	~1%
Decoupling MSSM	~-.0001%	~-2%	
Composite	~-3%	-(3-9)%	
Top partner	~-2%	~-2%	

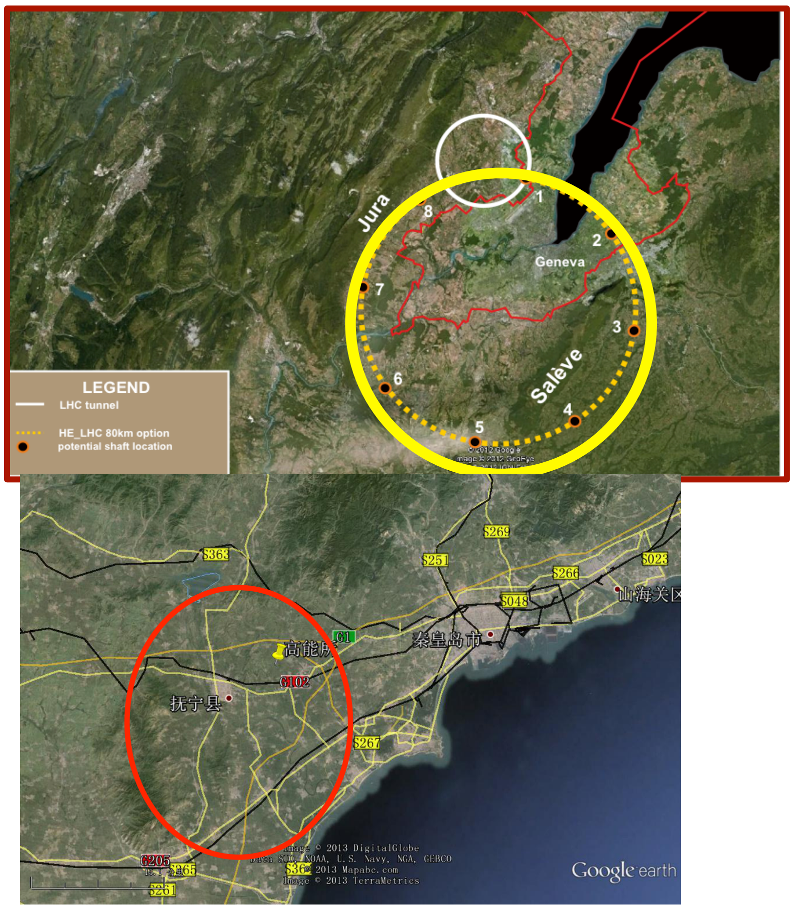
Big Dreams for the Future

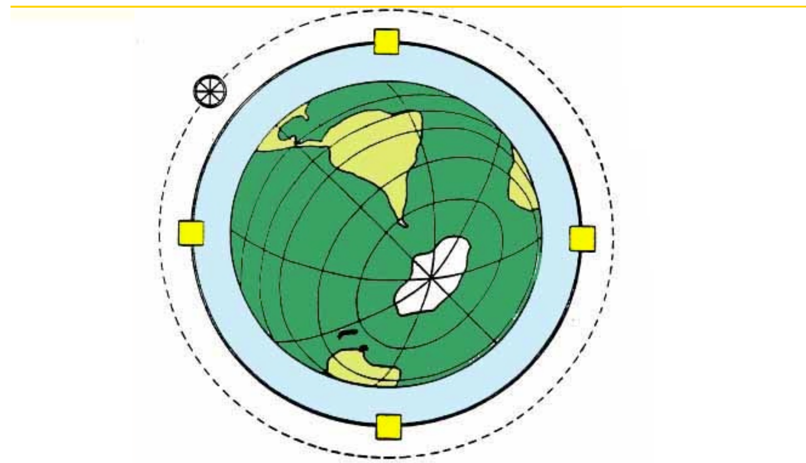
- 33, 70,.....,100 TeV pp collider
- 250/500/1000 GeV e^+e^- collider (ILC)
- 3 TeV e^+e^- collider(CLIC)
- Up to 10 TeV $\mu^+\mu^-$
- ***After the Higgs, no guaranteed discoveries***
  – But many questions remain suggesting new physics beyond the SM (flavor, dark matter….)

High energy machines are discovery machines

Super High Energy pp

Studies beginning at CERN and in China

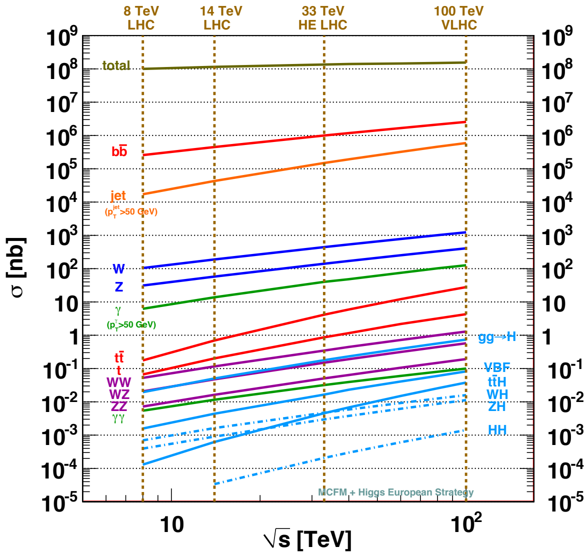




- Optimal energy for physics not yet determined
- 100 km ring with 15 T magnets gives $\sqrt{s}$=100 TeV
- Large cross sections for SM processes and BSM discovery

Bread and Butter SM Physics

- Large samples of W/Z/top/Higgs at high energy pp



Process	σ(100 TeV)/σ(14 TeV)
W	7
Z	7
WW	10
tt	33

Physics case for using these large samples is in its infancy

Higgs Properties

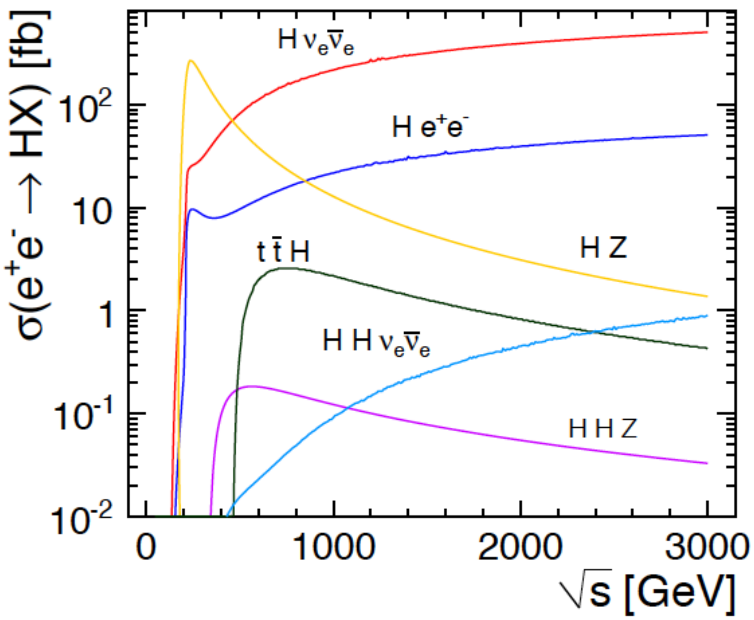
- Advantage of hadron machines:
  - Large cross sections at high energy pp

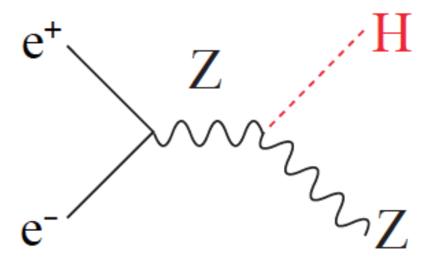
Higgs production:

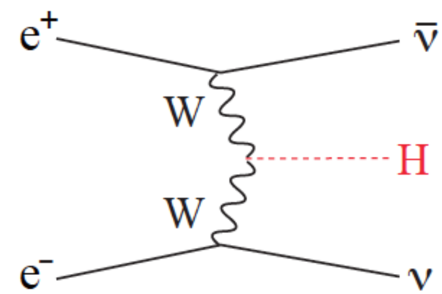
	$\sqrt{S}$=14 TeV	$\sqrt{S}$=33 TeV	$\sqrt{S}$=100 TeV
ggF	50.4 pb	178 pb	740 pb
VBF	4.4 pb	17 pb	82 pb
WH	1.6 pb	4.7 pb	16 pb
ttH	.62 pb	4.6 pb	38 pb
HH	.034 pb	.2 pb	1 pb

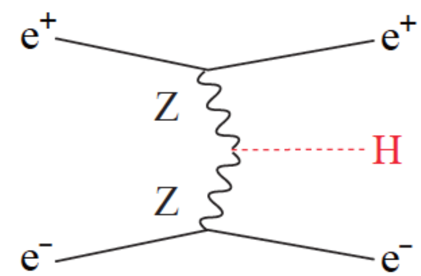
[Higgs cross section working group]

e^+e^- Colliders









Advantage: Coupling extractions don't need assumptions about total width

Start with Higgs Couplings

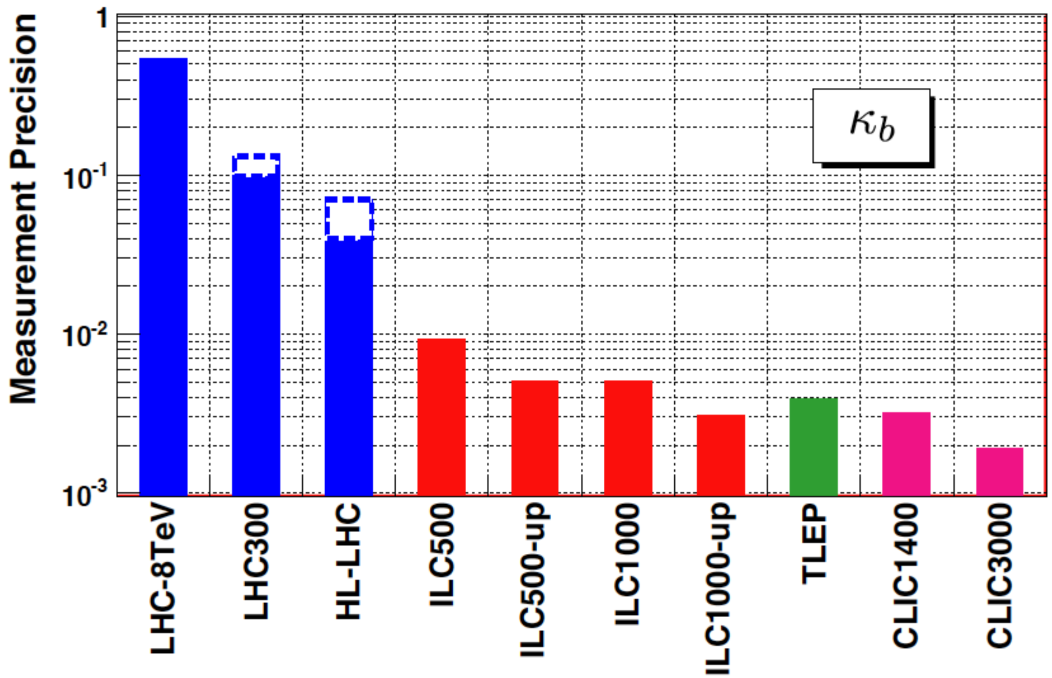
- Compare capabilities for extracting Higgs couplings at CLIC, $\gamma\gamma$, ILC, LHC (3000 fb^{-1}), 33 TeV LHC, 100 TeV LHC, μC, TLEP
- No value judgement about realities of machine parameters

Facility	HL-LHC	ILC	ILC(LumiUp)	CLIC	TLEP (4 IPs)	HE-LHC	VLHC
$\sqrt{s}$ (GeV)	14,000	250/500/1000	250/500/1000	350/1400/3000	240/350	33,000	100,000
$\int \mathcal{L}dt$ (fb^{-1})	3000/expt	250+500+1000	1150+1600+2500	500+1500+2000	10,000+2600	3000	3000
$\int dt$ (10^7s)	6	3+3+3	(ILC 3+3+3) + 3+3+3	3.1+4+3.3	5+5	6	6

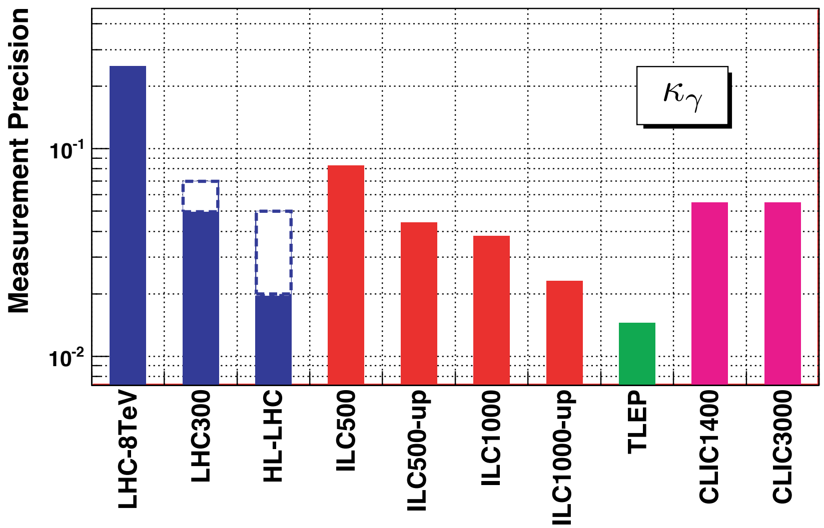
[Snowmass Higgs Working Group Report, arXiv:1310.8361]

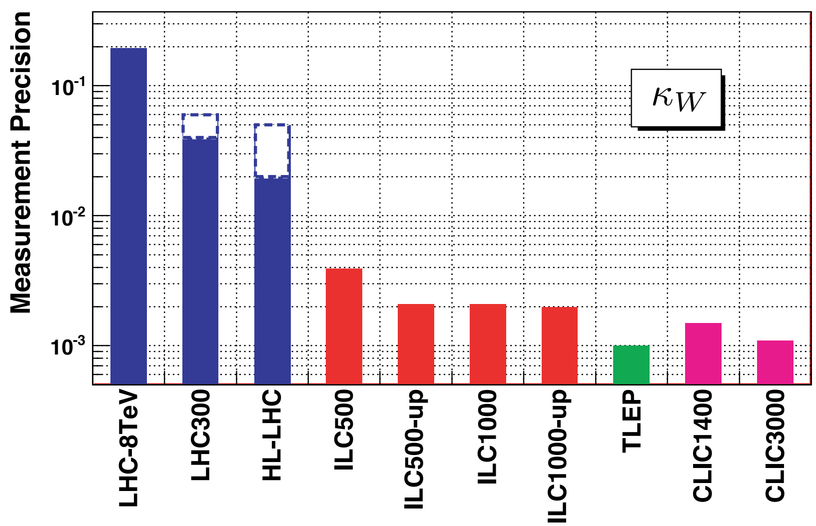
Examples of Comparisons

- Redo e^+e^- fits with SM Γ_H restrictions and 7 parameter fits

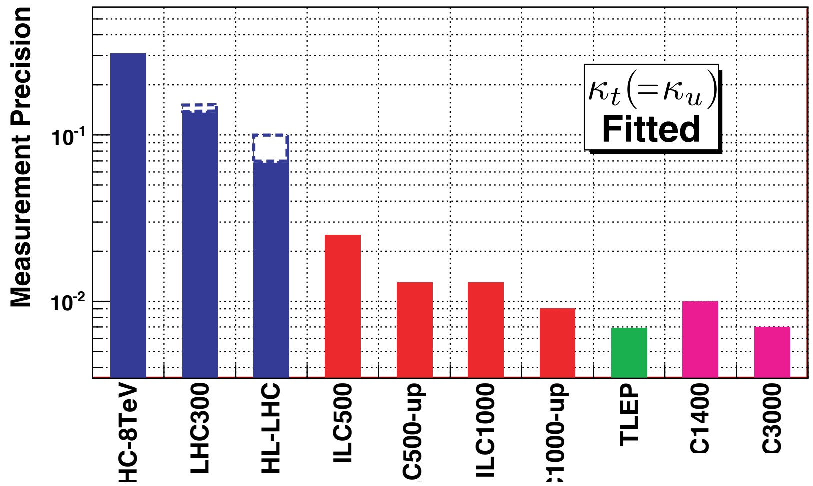


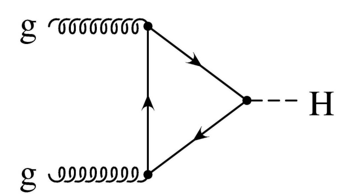
* This assumption not needed for e^+e^-

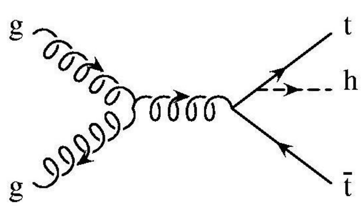

Measurement Precision
10^{-1}
10^{-2}
κ_γ
LHC-8TeV
LHC300
HL-LHC
ILC500
ILC500-up
ILC1000
ILC1000-up
TLEP
CLIC1400
CLIC3000

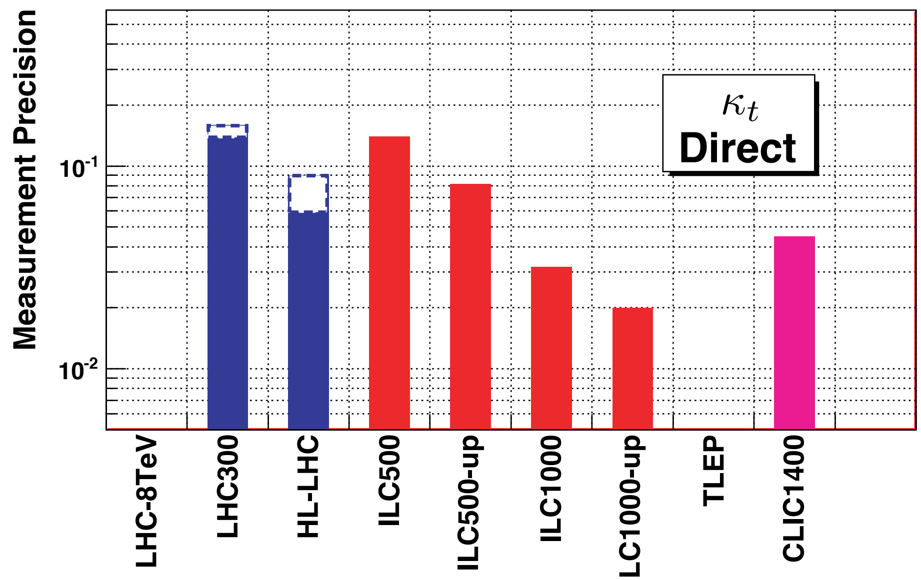

Measurement Precision
10^{-1}
10^{-2}
10^{-3}
κ_W
LHC-8TeV
LHC300
HL-LHC
ILC500
ILC500-up
ILC1000
ILC1000-up
TLEP
CLIC1400
CLIC3000

Top Yukawa Particularly Interesting



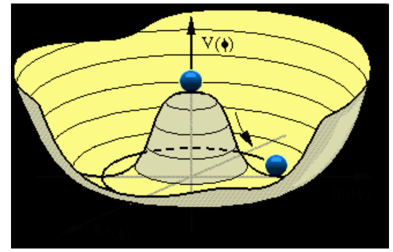






Does the Higgs come from the SM Potential?

$$V = \frac{M_H^2}{2} H^2 + \frac{M_H^2}{2v} H^3 + \frac{M_H^2}{8v^2} H^4$$

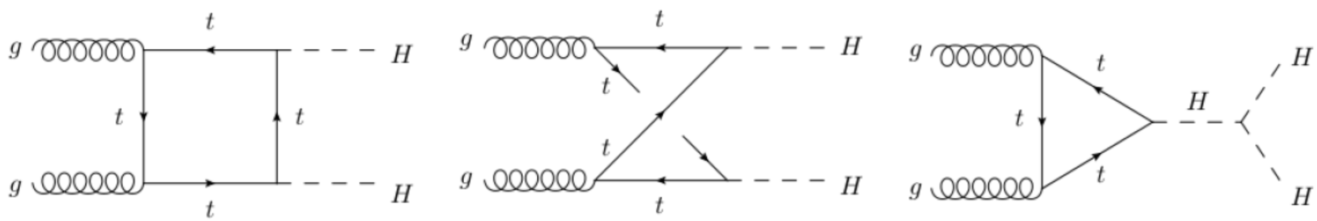


- Need to measure HHH and HHHH couplings
- HHH coupling can be measured with HH production

BSM models can change the HHH and HHHH couplings by factors ~ 10-20%*

*Models are restricted by requiring single H production to have experimentally measured value

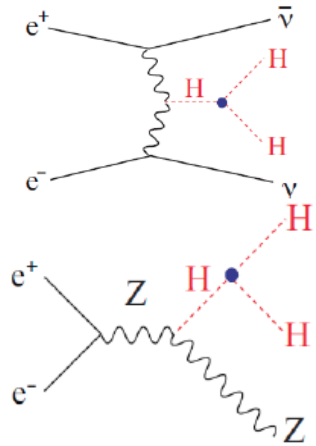
Higgs Self Coupling

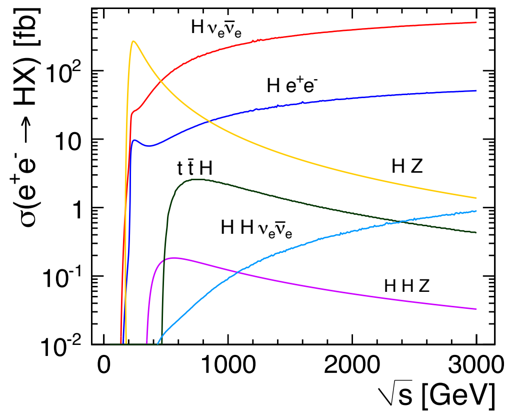


- Sensitive to HHH coupling and new particles in loops
- Small rates at LHC:
  - $bb\gamma\gamma$ gives 3σ with 3 ab^{-1} (270 events with 3 ab^{-1})
  - 30% measurement of λ_{HHH} with 2 experiments for SM
  - 8% with 100 TeV pp

[Guesstimate from Snowmass Higgs Report, arXiv:1310.8361;
Yao, Snowmass study, arXiv: 1308.6302]

e^+e^- machines have low rates for HH





	ILC500	ILC500-up	ILC1000	ILC1000-up	CLIC1400	CLIC3000
$\sqrt{s}$ (GeV)	500	500	500/1000	500/1000	1400	3000
$\int \mathcal{L}dt$ (fb^{-1})	500	1600‡	500+1000	1600+2500‡	1500	+2000
$P(e^-, e^+)$	$(-0.8, 0.3)$	$(-0.8, 0.3)$	$(-0.8, 0.3/0.2)$	$(-0.8, 0.3/0.2)$	$(0, 0)/(-0.8, 0)$	$(0, 0)/(-0.8, 0)$
$\sigma\,(ZHH)$	42.7%		42.7%	23.7%	–	–
$\sigma\,(\nu\bar{\nu}HH)$	–	–	26.3%	16.7%		
λ	83%	46%	21%	13%	28/21%	16/10%

μ Collider $\delta\lambda_{HHH}$ < 10% at 6 TeV

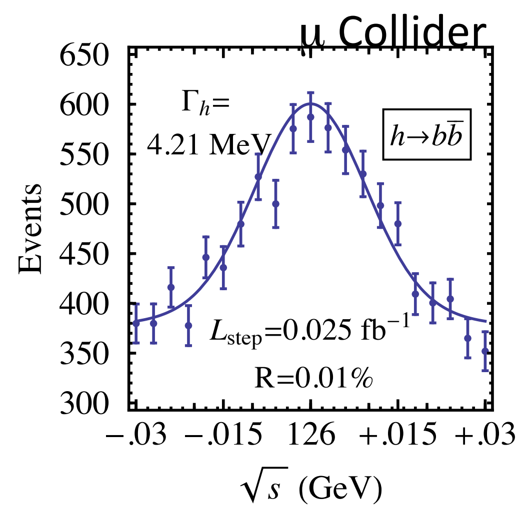
Higgs Width/Mass Measurements

	ILC1000	CLIC	TLEP (4 IP)	μC
√S (GeV)	250/500/1000	350/1400/3000	240/350	126
L (fb^{-1})	250+500+1000	500+1500+2000	10,000+2600	
ΔM_H (MeV)	32	20*	7	.06
Γ_H	5.6%	4%*	0.6%	4.3%

- $\mu^+\mu^-$ collider: Energy scan gives M_H, Γ_H
  - s-channel with 4.2 fb^{-1}

    ΔM_H = .06 MeV, $\Delta\Gamma_H$ = .18 MeV

    HL-LHC ΔM_H=50 MeV



[Table from Snowmass Higgs Report, arXiv:1310.8361; Figure from Han, Liu, arXiv: 1210.7803]

*New since Snowmass

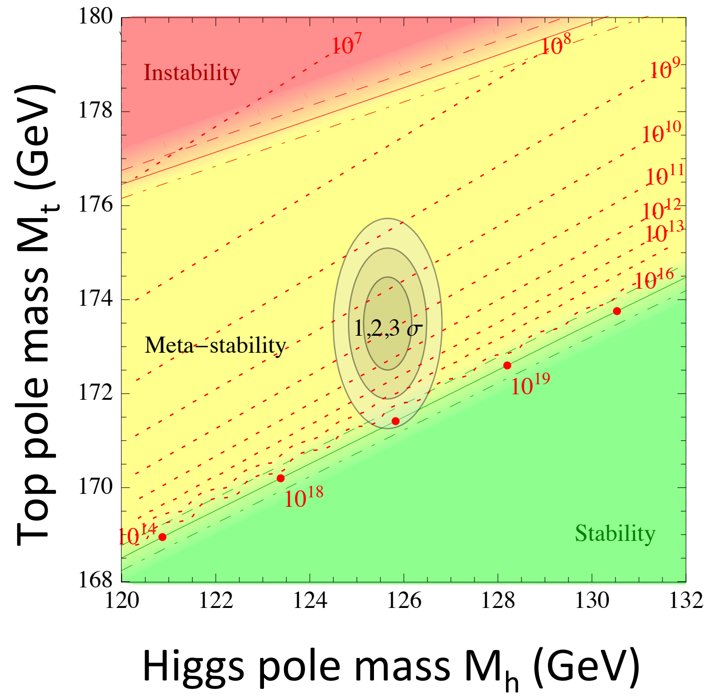
Why We Care About M_h

- The Higgs sector is perturbative $\lambda = \dfrac{M_h^2}{2v^2}$

$$V = -\frac{\mu^2}{2} H^2 + \frac{\lambda}{4} H^4$$

$$\lambda \sim .13, \mu \sim 90\ GeV$$

- We can sensibly calculate to high scales
  - *Assuming no new physics!*
- Is M_h=125-126 GeV special?

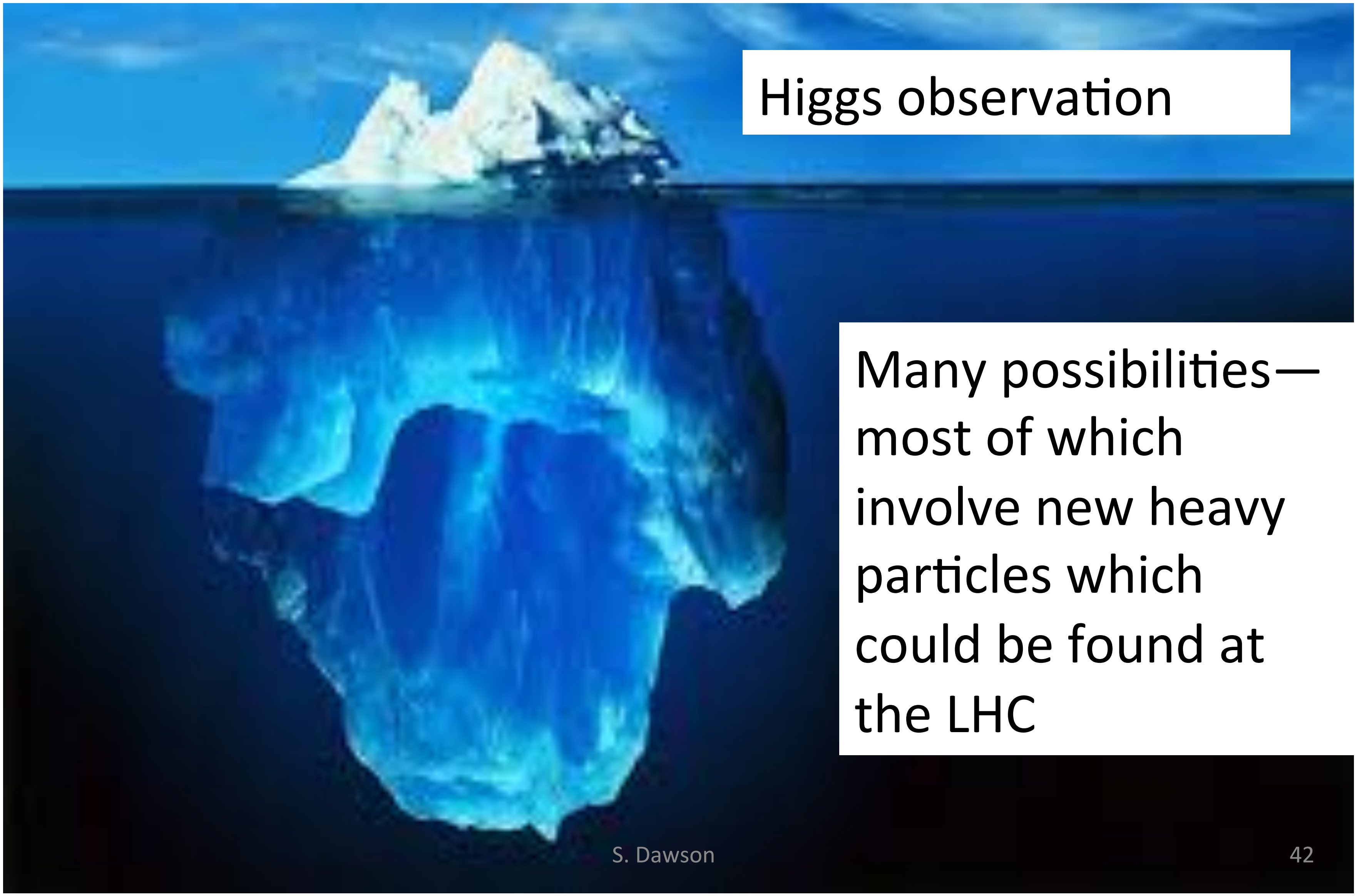


[Buttazzo et al, 1307.3536]

Are we done? NO

- Standard Model is beautiful and explains Higgs measurements
- But…..
  - It doesn't explain the pattern of masses
    - Why is $M_{top} >> m_{bottom}$?
    - Why are neutrinos so light?
  - It doesn't explain dark matter or dark energy
  - Many models proposed to explain various features

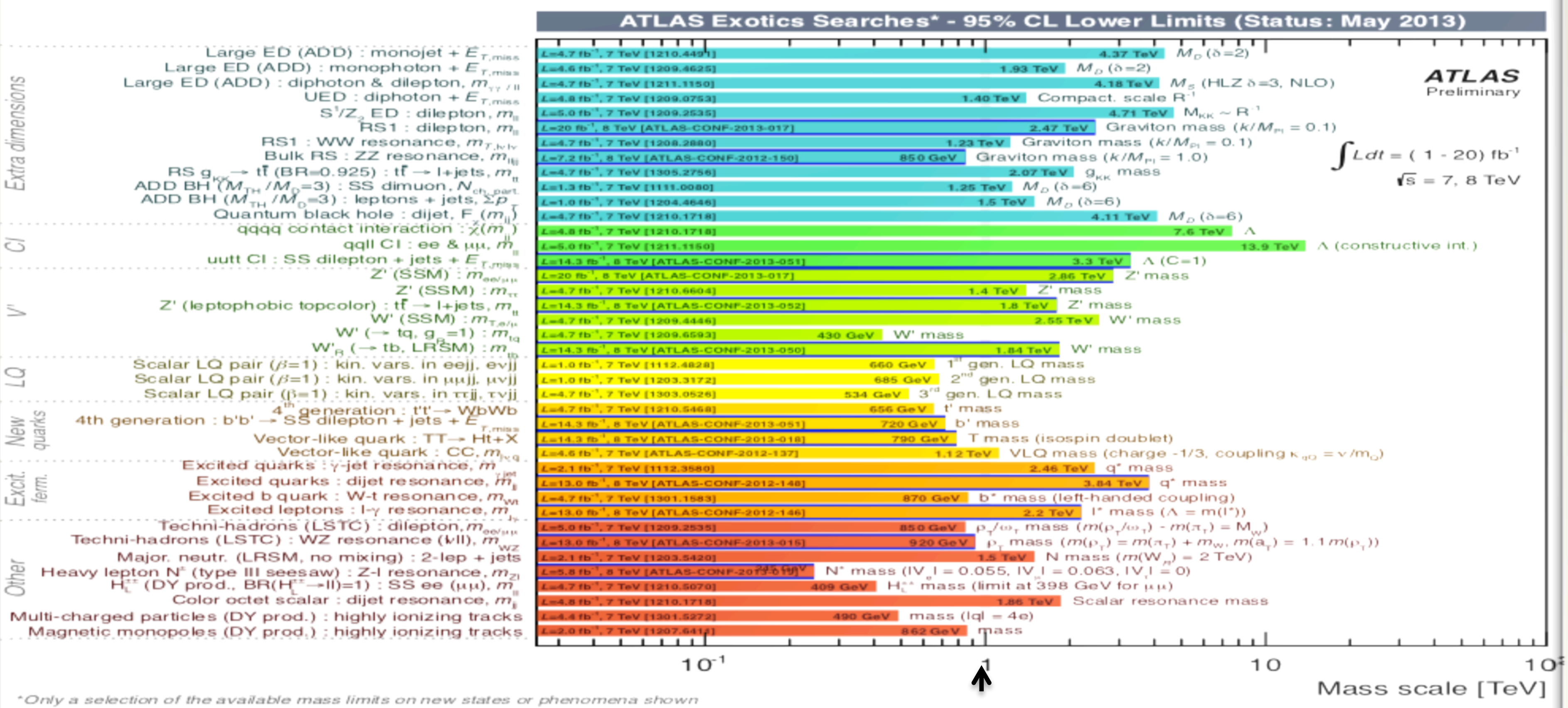
We expect something beyond Higgs



Higgs observation

Many possibilities—most of which involve new heavy particles which could be found at the LHC

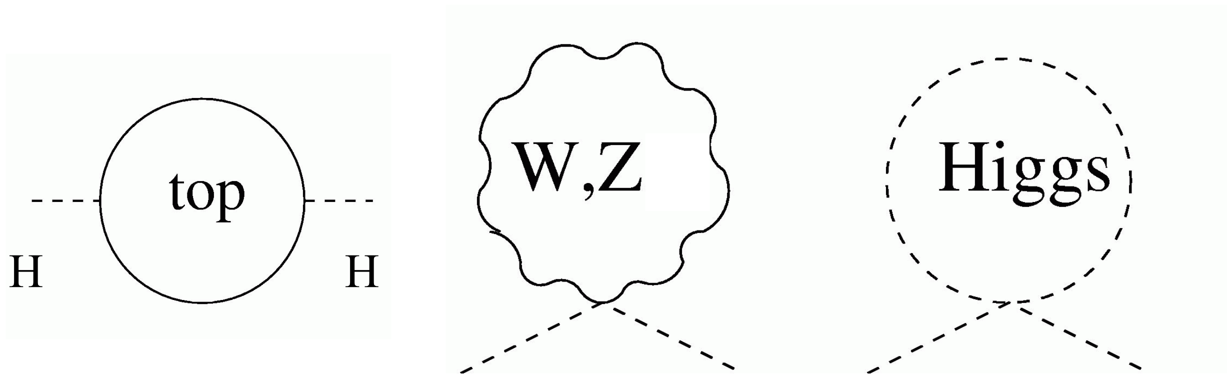
Many Possibilities excluded by LHC



1 TeV

The proof by exhaustion school of physics!

Pinpointing the Scale of New Physics



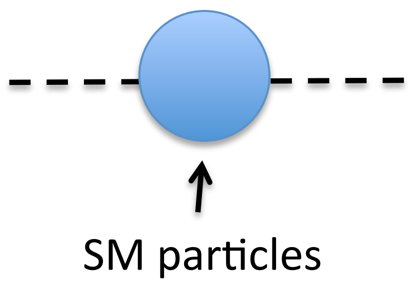
- Higgs mass grows with high scale, Λ (*a priori* Λ=M_{pl})

δM_H ~ 125 GeV requires Λ ~ 600 GeV

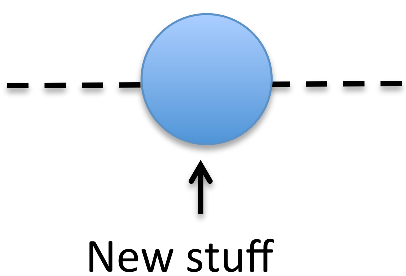
- Argument suggests new physics at (?) TeV scale
- Is scale 1,2,....10 TeV?

The Naturalness Connection

- Generically, solutions to naturalness involve new particles, which lead to deviations in Higgs couplings



$$\delta M_H^2 \sim -(125\ GeV)^2 \left(\frac{\Lambda}{600\ GeV}\right)^2$$

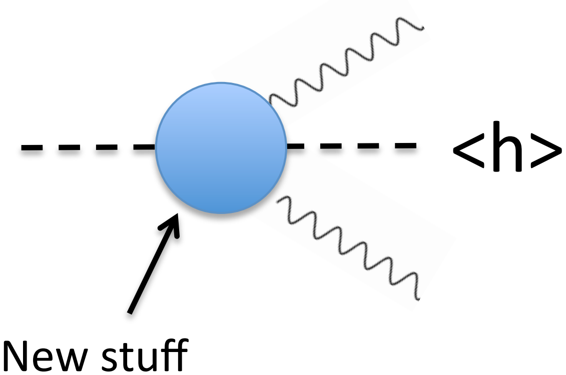


$$\delta M_H^2 \sim +(125\ GeV)^2 \left(\frac{\Lambda}{M_{new}}\right)^2$$

For this cancellation to work, new stuff can't be too much above TeV scale

The Naturalness Connection

- Generically, solutions to naturalness involve new particles, which lead to deviations in Higgs couplings



MSSM light stops generically contribute (no mixing):

$$\kappa_g^2 = \frac{\sigma(gg \to h)}{\sigma(gg \to h)\mid_{SM}} \sim 1 + \left(\frac{700\ GeV}{\tilde{m}_t}\right)^2 3\%$$

Target precision < 3%

As LHC limits on new particles increase, target precision decreases

New Physics in Loops

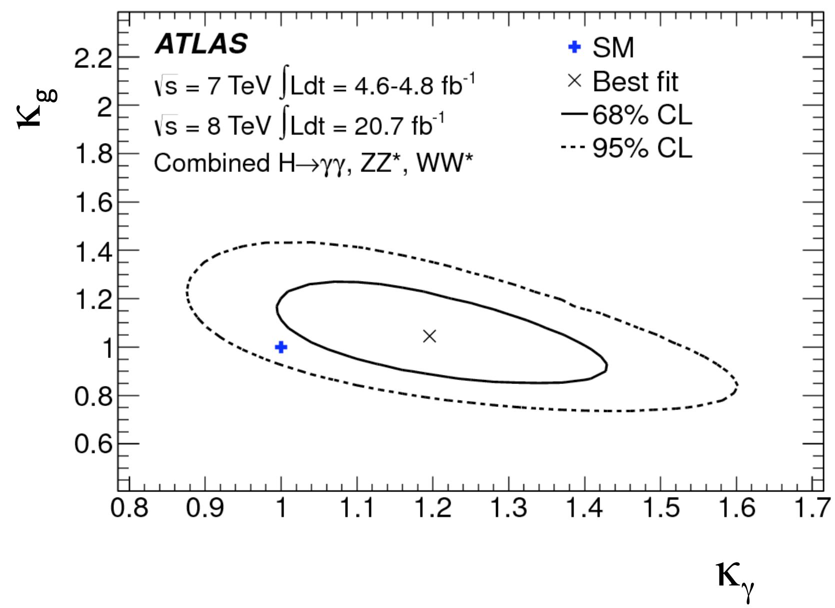
- Might expect to see deviations in loop processes first
  - New heavy particles could make large contributions

ATLAS @68% CL

$k_g = 1.04 \pm 0.14$

$k_\gamma = 1.20 \pm 0.14$

The hope that we can discover new physics by observing large deviations in Higgs processes is under tension



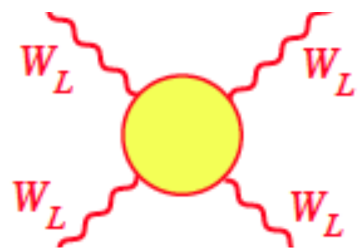
The LHC 14 TeV run should clarify this!

Precision Measurements and BSM Physics

- Precision Higgs measurements can point to the existence of new physics, but can't tell you what it is
  - SM framework allowed predictions for m_t and M_H in terms of well defined theory and observables
  - Different case now: Pattern of deviations from SM can suggest possibilities, but there is no standard BSM
  - In some cases, sensitivity to very high scales, but not guaranteed
- High energy machines directly produce particles associated with new physics

If no new particles at LHC

- Effective Lagrangians can be used to describe physics
  - Construct interactions which respect SU(2) x U(1) symmetry
  - Expand in powers of s/Λ^2: $L \sim L_{SM}+\Sigma f_i\, O_i/\Lambda^2+ \ldots.$
- Effects grow with energy
- Precision measurements of VBF at CLIC, high energy pp



[Electroweak Snowmass Report, arXiv: 1310.6708]

Neutrinos and the Higgs

- High energy effects of new physics suppressed by large masses
- Systematic classification of new in terms of 1/Λ

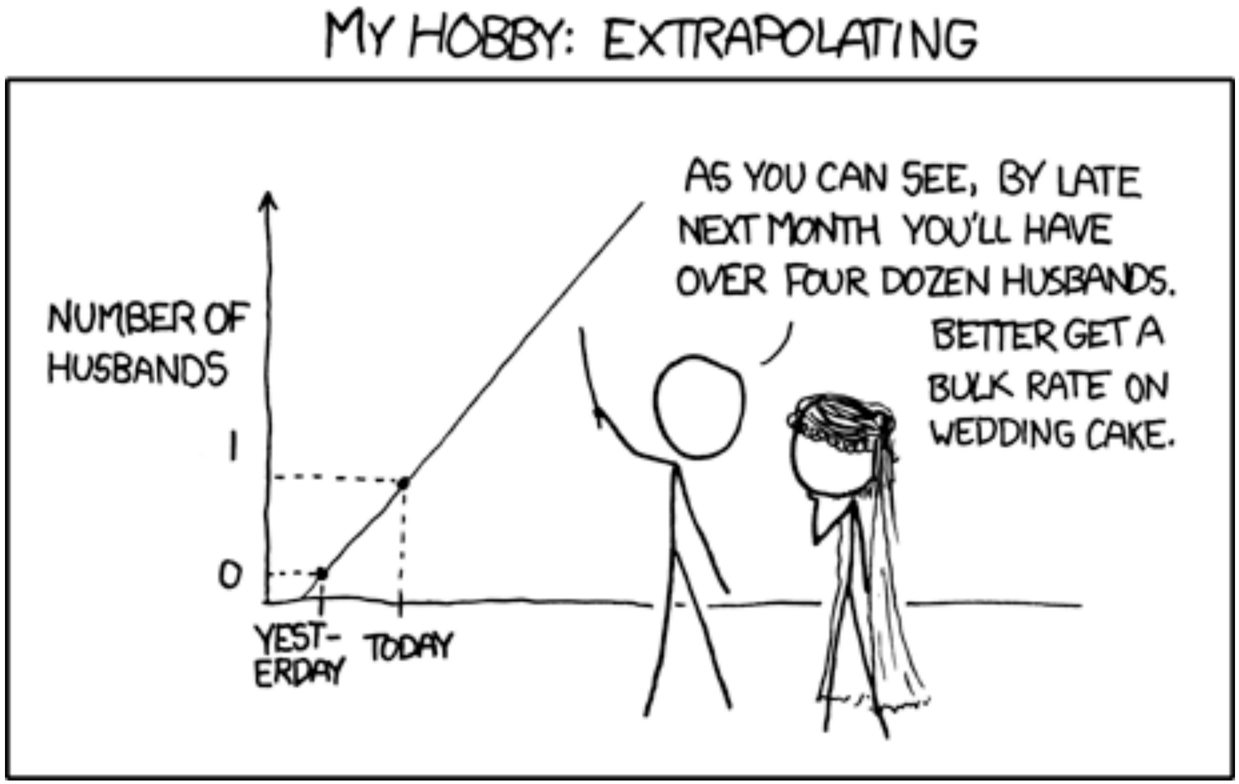
$$L \sim L_{SM} + \frac{L_5}{\Lambda} + \frac{L_6}{\Lambda^2} + \ldots .$$

- In the Standard Model, no neutrino masses
  - Only one dimension 5 operator
  - Effective interactions naturally contain Majorana neutrino masses

$$L_5 = \frac{1}{\Lambda}(L\phi)(L\phi) \rightarrow \frac{1}{\Lambda}(L < h >)(L < h >) = \frac{v^2}{\Lambda}\nu\nu$$

Conclusions

- Can we find new physics by precision measurements of Higgs couplings?
  - *To start, we have to get SM theory and PDFs under better control*
- I haven't found examples where lever arm gets you to multi-TeV scale BSM physics from precision Higgs measurements
  - This argues for searching for direct production of new particles
    - *However….. Predictions are always tricky*


MY HOBBY: EXTRAPOLATING
NUMBER OF HUSBANDS
1
0
YEST-ERDAY
TODAY
AS YOU CAN SEE, BY LATE NEXT MONTH YOU'LL HAVE OVER FOUR DOZEN HUSBANDS. BETTER GET A BULK RATE ON WEDDING CAKE.